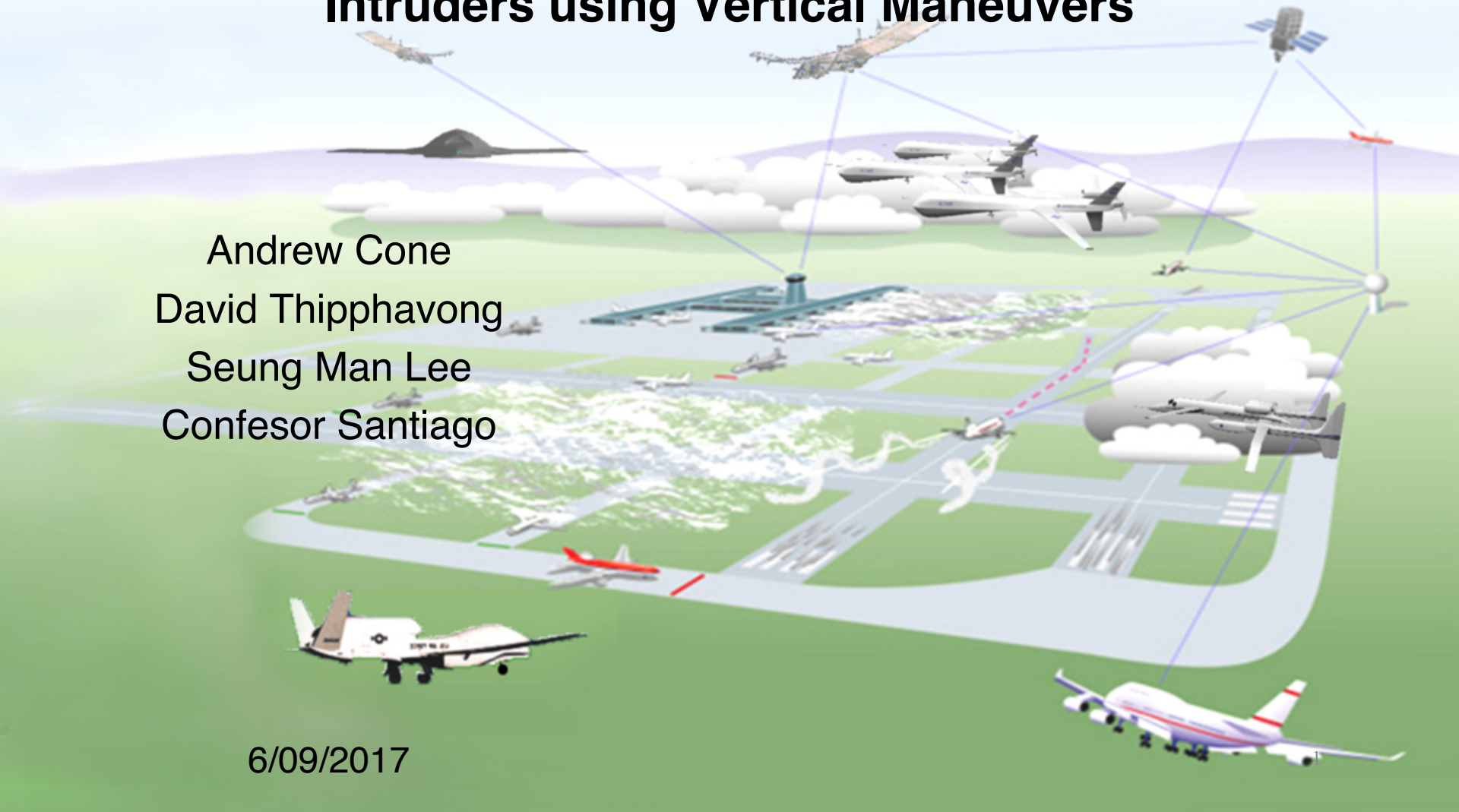
National Aeronautics and Space Administration

UAS Well Clear Recovery against Non-Cooperative Intruders using Vertical Maneuvers



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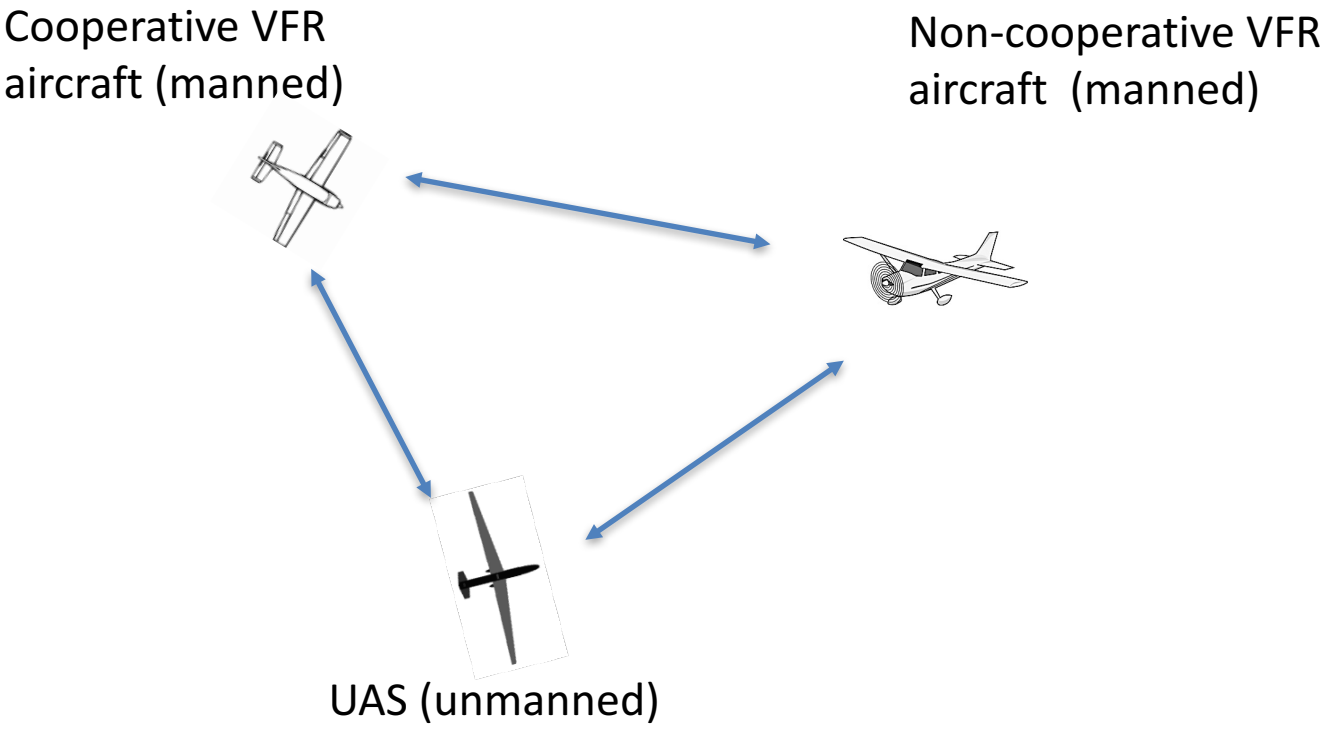
Outline

- Non-Cooperative VFR
  - What are they and why is there a problem in this context?
- DAA Well Clear Recovery
  - What is Detect-and-Avoid (DAA) well clear?
  - How does a DAA system respond to losing well clear?
- Research Question
- Experimental Design
- Primary Metric
- Results
- Special Case
- Conclusions

Non-Cooperative VFR Aircraft

- These are VFR aircraft without an active transponder

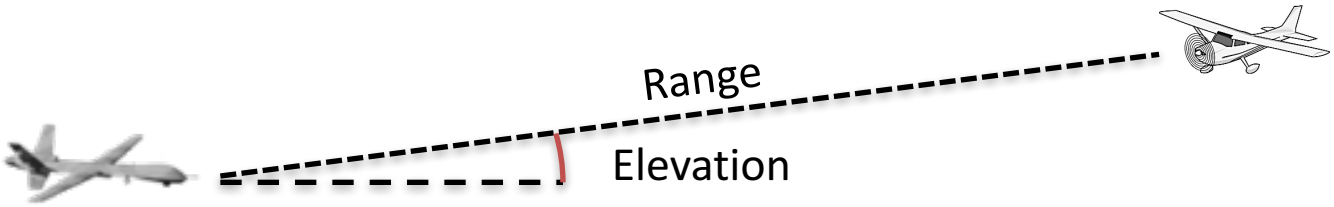
- Current plans require air-to-air radar on board UAS



Non-cooperative VFR and Air-to-Air Radar Errors

- **Vertical rate estimations for non-cooperative VFR aircraft can have large errors that are difficult to reduce**

- For a UAS using radar, other aircraft's altitude is relative, based off elevation and distance



Detect and Avoid (DAA) Well Clear

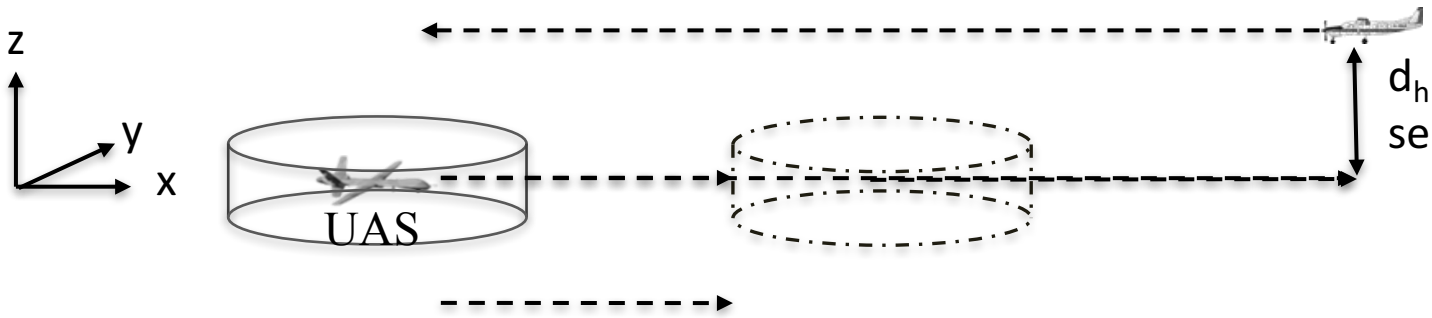
- All aircraft are required to remain “well clear” from other aircraft (14CFR Part 91, §91.113)

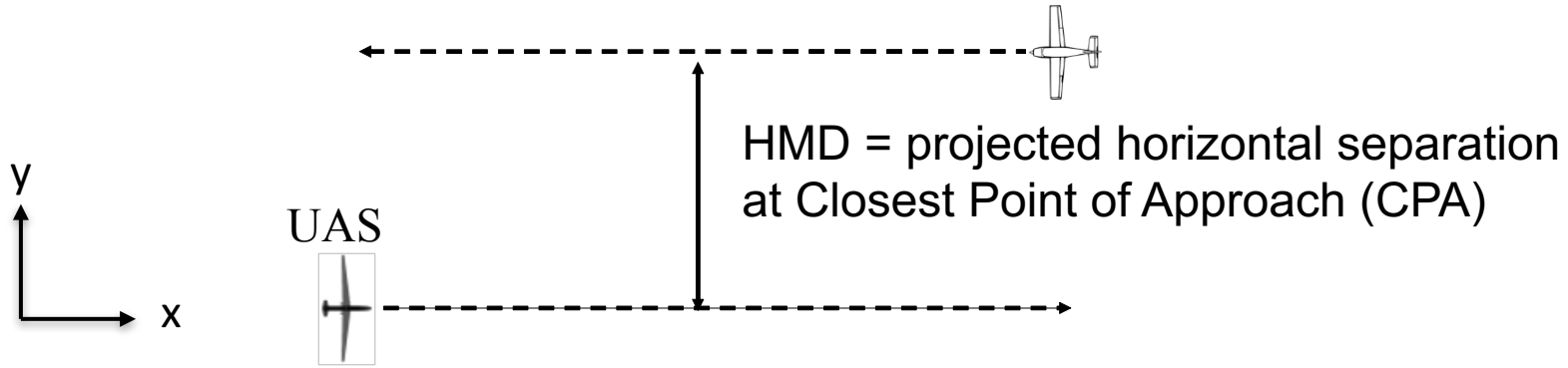
- RTCA Special Committee - 228 was responsible for creating Minimum Operational Performance Standards (MOPS) for DAA systems

  – Includes formal definition of DAA well clear

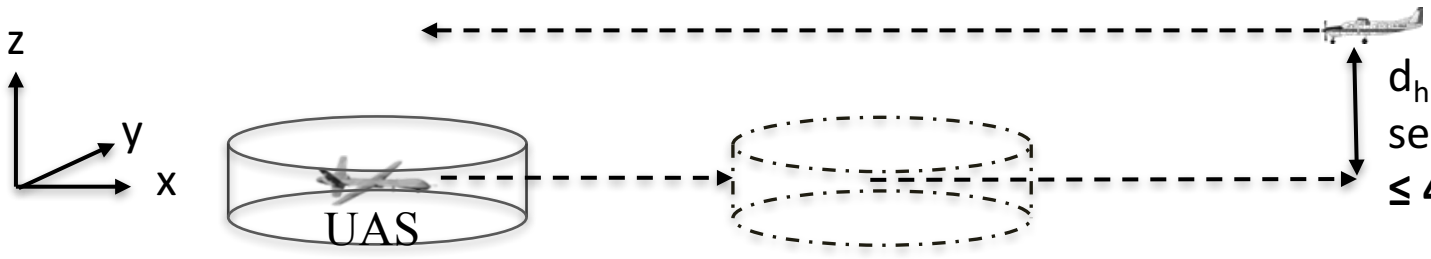
  – Includes specifications for the components of DAA systems

DAA Well Clear Definition (1)



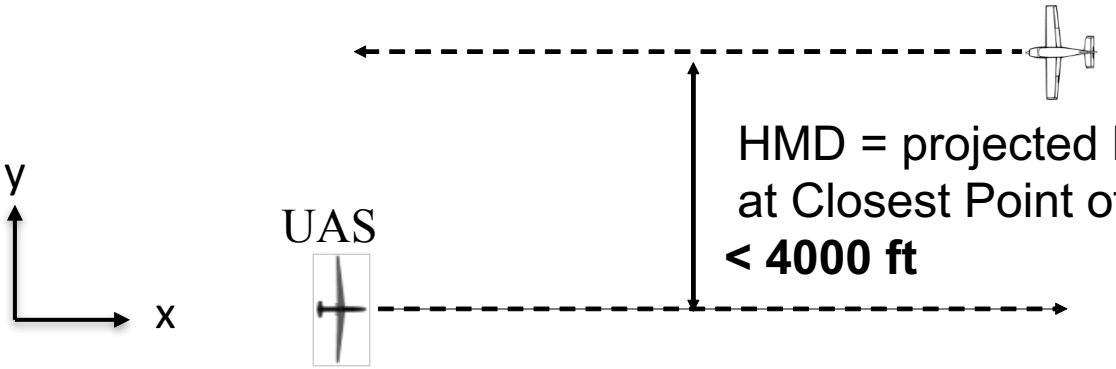


DAA Well Clear Definition (1)



d_h = current vertical separation
≤ 450 ft

τ_{mod} (modified tau) ≈ time to CPA
< 35 s



HMD = projected horizontal separation at Closest Point of Approach (CPA)
< 4000 ft

DAA Well Clear Recovery

- **DAA well clear recovery (WCR) refers to guidance offered to the UAS pilot in order to regain DAA well clear**
  - DAA system will offer a vertical and a horizontal maneuver to the UAS pilot
  - Must be offered when DAA well clear is lost
  - Can be offered as soon as loss of DAA well clear unavoidable
- Estimating separation from vertical well clear recovery maneuvers is difficult when the other aircraft is non-cooperative

Research Question

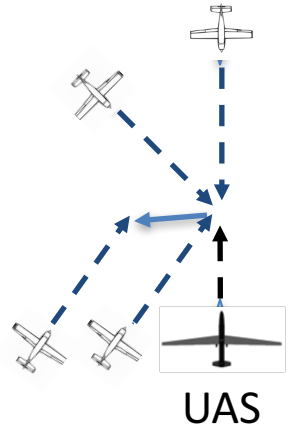
- When should a UAS pilot receive vertical DAA well clear recovery guidance for an encounter with a non-cooperative VFR aircraft?
  - Current approach in the MOPS accounts for:
    - Vertical rate error and vertical position error for non-cooperative VFR
    - Relative altitude between UAS and non-cooperative VFR
    - Current vertical rate of UAS and vertical rate available for well clear recovery maneuver
- **UAS is allowed to maneuver vertically when it can outrun the propagation of the vertical error of the non-cooperative VFR**

Experiment Design

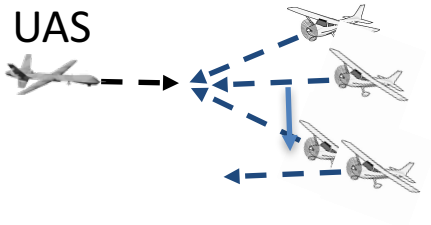
- Fast-time simulation with pair-wise encounters
  - Each encounter would result in a loss of DAA well clear if no action taken
  - UAS not permitted to maneuver until the guidance algorithm determined that a loss of DAA well clear was unavoidable
  - Combinatorial encounter matrix with 108,000 encounters (Two sets of 54,000)
    - One set allowed vertical WCR maneuvers, the other allowed only horizontal maneuvers
    - Encounter matrix populated by different encounter geometries, UAS initial states, and intruder initial states
- Simulation was an exploratory check of suitability of vertical rate error thresholds (for restricting DAA well clear recovery guidance)

Encounter Geometries

Horizontal



Vertical



Encounter Matrix

Parameter Type	# Values	Values
UAS ground speed	2	50, 200 kts
Intruder ground speed	2	70, 170 kts
Intruder heading	5	0, 45, 90, 135, 180 deg
Intruder vertical speed	5	-2000, -1000, 0, 1000, 2000 ft/min
UAS trial plan maneuver turn rate	2	1.5, 3 deg/sec
UAS trial plan climb/descent rate	6	(500/500), (1000/1000), (1500/1500), (2000/2000), (500/2000), (2000/500) ft/min
Horizontal intruder trajectory shifting	9	0 nmi: (x,y) = (0,0) 0.2 nmi: (x,y) = (0.2, 0), (-0.2, 0), (0, 0.2), (0, -0.2) 0.5 nmi: (x,y) = (0.5, 0), (-0.5, 0), (0, 0.5), (0, -0.5)
Vertical intruder trajectory shifting	5	-400, -200, 0, 200, 400 ft

Radar Model

- Radar and tracker models incorporated into simulation
  - Radar azimuth limit of +/- 110 degrees
  - Radar elevation limit of +/- 20 degrees
  - Radar model noise levels tuned to an early flight test

- Vertical rate estimations using air-to-air radar and tracker*
  - Median error: -230 fpm
  - Median absolute error: 433 fpm
  - Edges of distribution extend outside +/- 1000 fpm

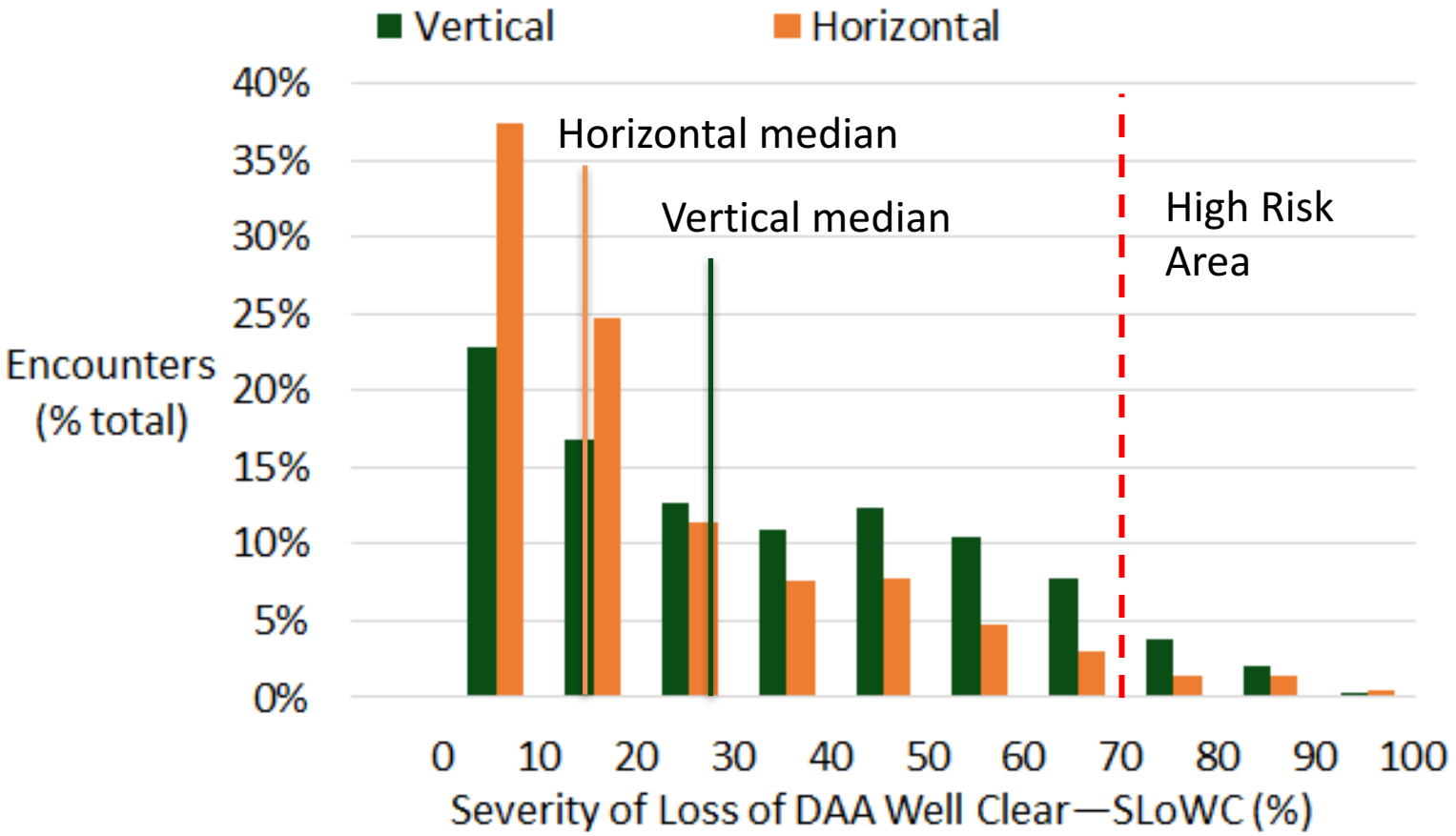
*Tracker used in study was a prototype and is in its own development cycle

Primary Metric

- Maximum severity of a loss of DAA well clear (SLoWC)
  - Produces a single number representing separation
  - 0% is outer edge of a loss of well clear
  - 100% is zero separation (collision)

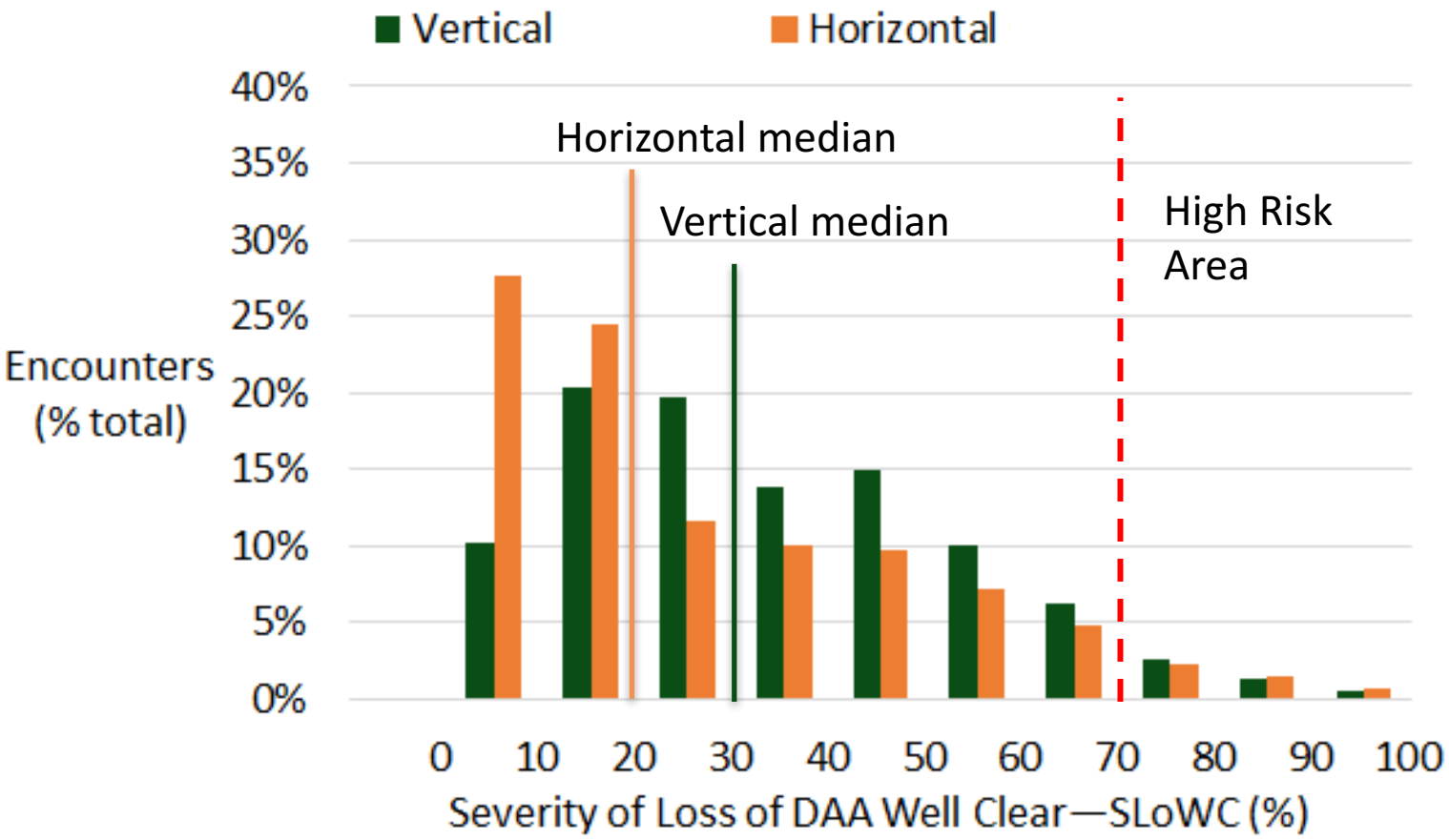
Results: Severity of Loss of DAA Well Clear

500 fpm UAS (Vertical vs Horizontal Maneuvers)



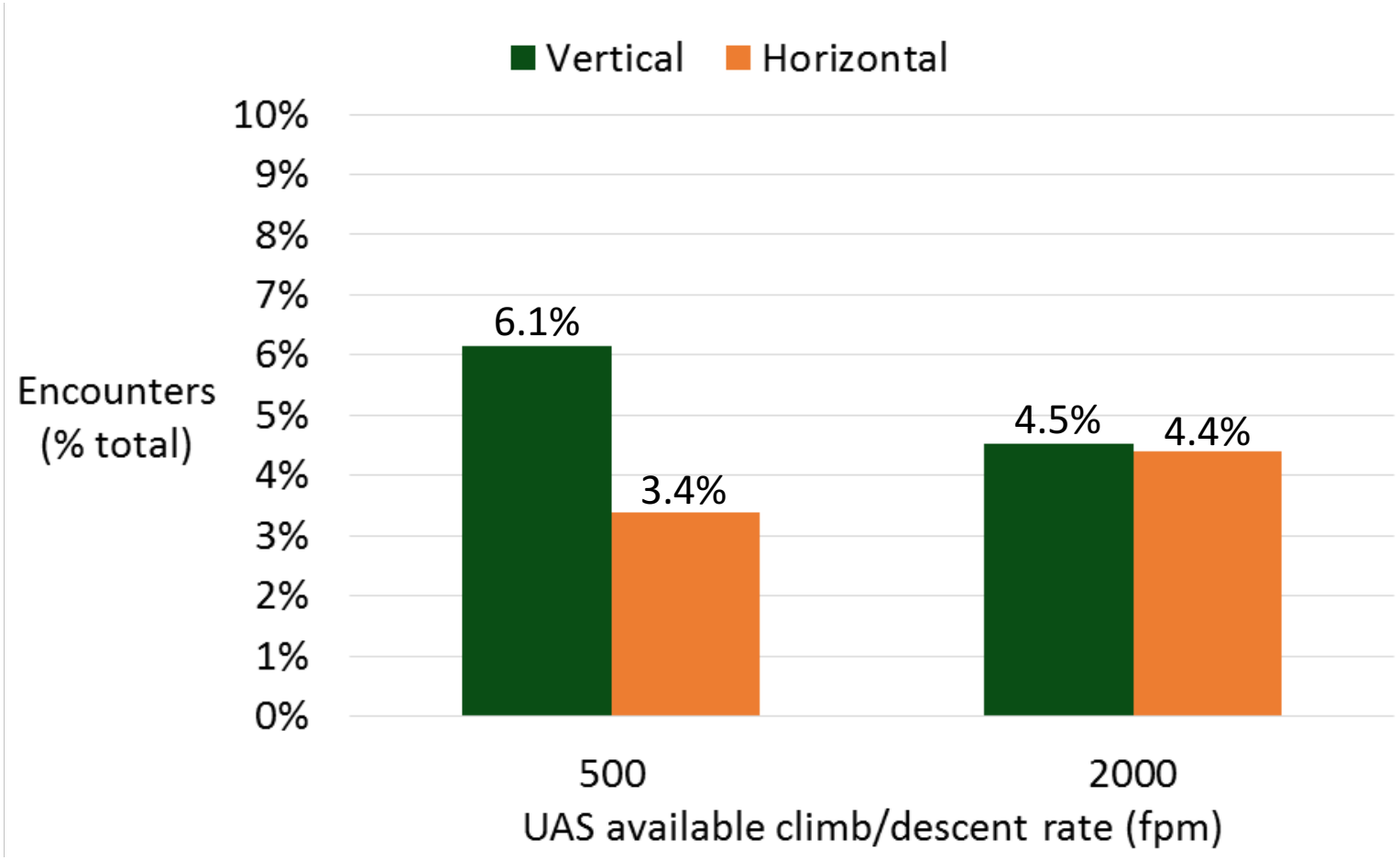
Median severity of encounters is lower for horizontal maneuvers

2000 fpm UAS (Vertical vs Horizontal Maneuvers)



Median severity of encounters is lower for horizontal maneuvers

High Risk Encounters

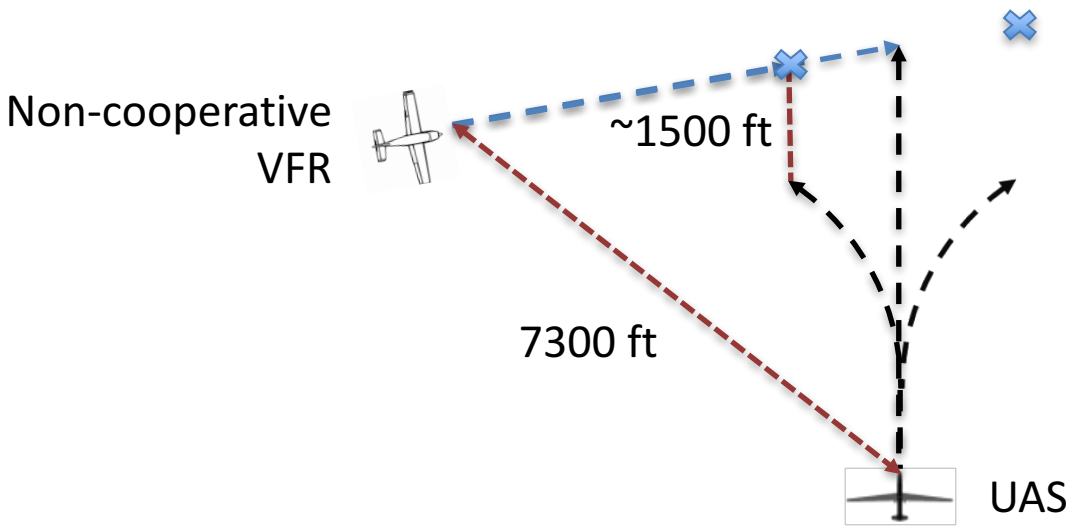


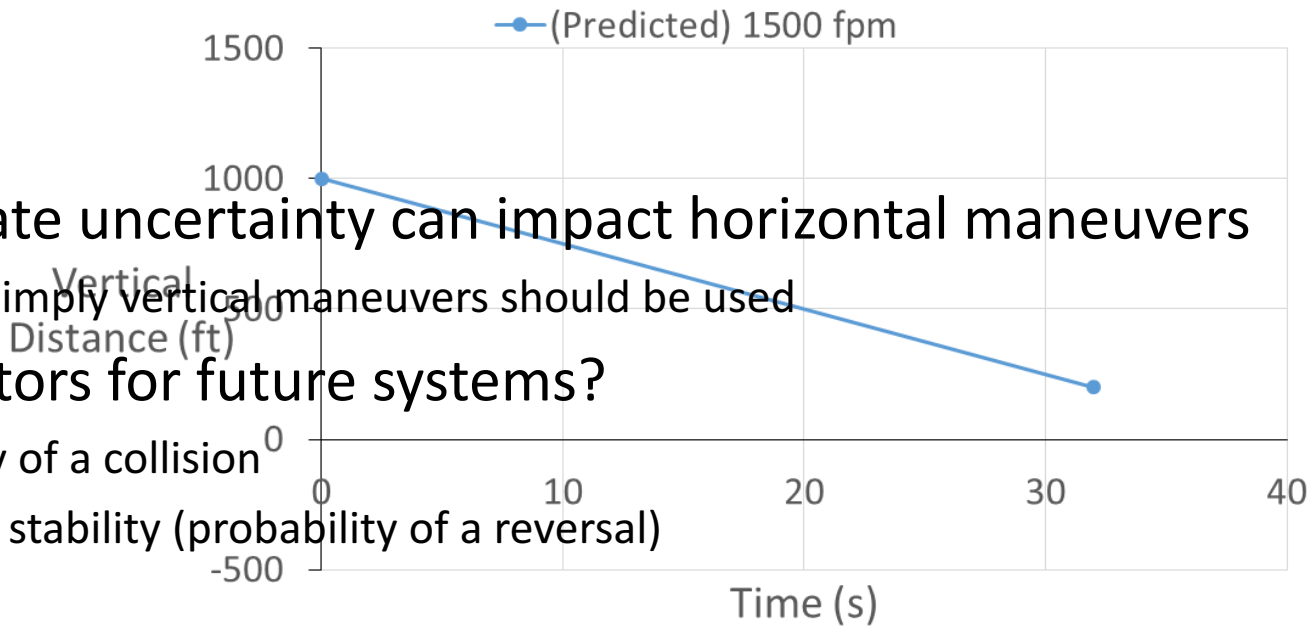
The percentage of encounters with high risk of collision is sensitive to vertical rate available to a UAS for DAA well clear recovery maneuvers

Special Case: Horizontal Turn Ambiguity

- Some encounter geometries could be intrinsically difficult to resolve using horizontal maneuvers
  - Crossing encounters with non-cooperative VFR descending or climbing
  - Non-cooperative VFR not maneuvering
- Likelihood of encounters outside of scope for this work
- These encounters do not necessarily have more separation when vertical maneuvers used

Horizontal Turn Ambiguity Nominal Example





- Vertical rate uncertainty can impact horizontal maneuvers
  - Does NOT imply vertical maneuvers should be used
- Other factors for future systems?
  - Probability of a collision
  - Maneuver stability (probability of a reversal)

Conclusions

- DAA well clear recovery guidance offered to UAS pilot for non-cooperative intruder now accounts for UAS vertical rate performance

- There are still potential areas for study: Horizontal turn ambiguity due to intruder vertical rate prediction error

Questions?

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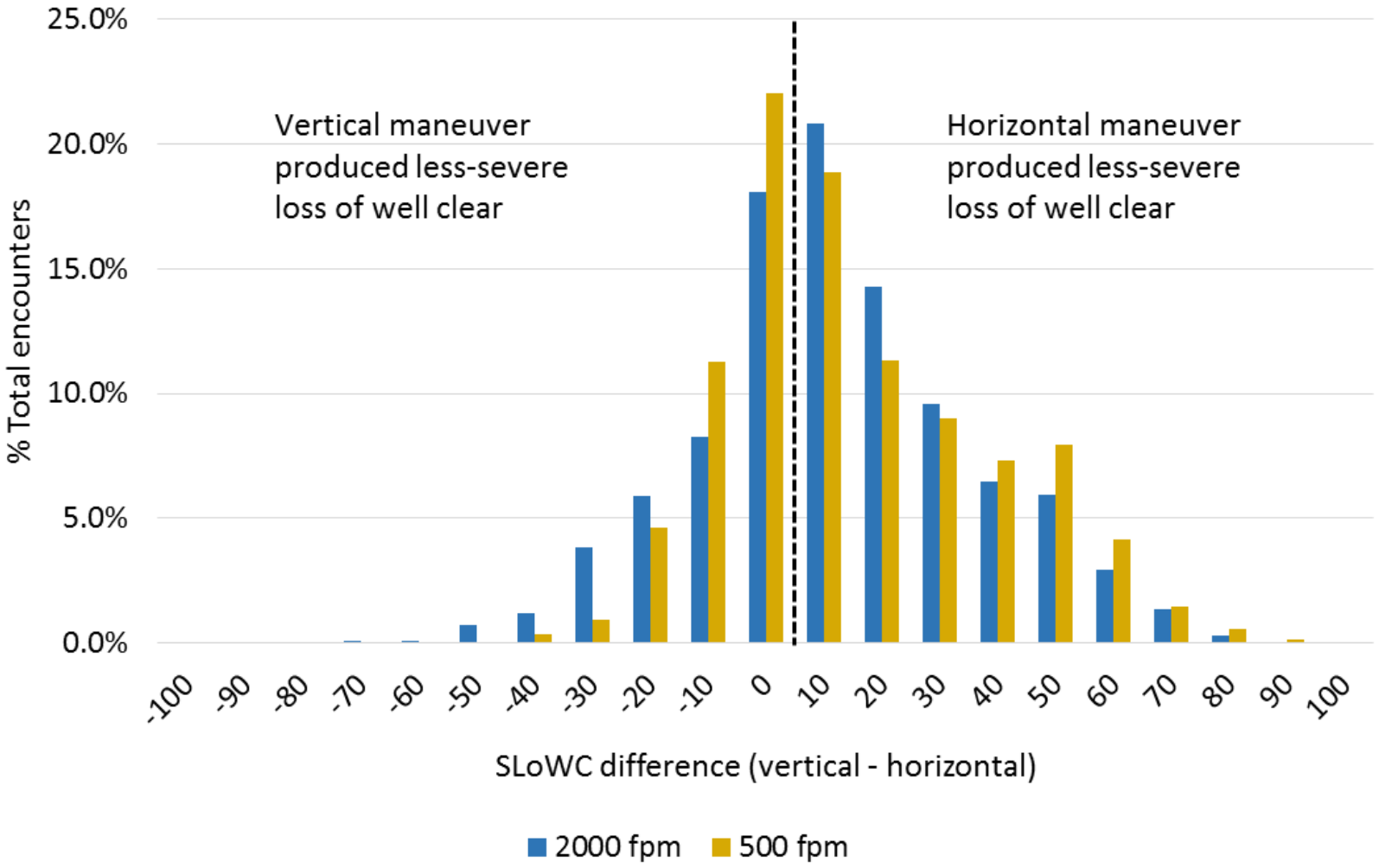
- Paired encounters
  - In one encounter, UAS used vertical maneuver, in other it used horizontal
    - Only reporting cases where both maneuvers were started at the same time
    - Simulation is mitigated, so reversals and maneuver adjustments were permitted
- Results show
  - High performance UAS had greater percentage of encounters where vertical maneuvers had a SLoWC that was at least 20% lower
  - Low performance UAS had a greater percentage of encounters where horizontal manuvers had aSLoWC that was at least 30% lower
  - The percentage of encounters where vertical maneuvers produced a lower SLoWC was about the same (38% to 39%).
- For all UAS performance levels tested, there were similar numbers for the percentage of encounters where vertical maneuvers had lower SLoWC


25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
% Total encounters
Vertical maneuver produced less-severe loss of well clear
Horizontal maneuver produced less-severe loss of well clear
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100
SLoWC difference (vertical - horizontal)
2000 fpm
500 fpm